

Probe Measurements and Potential Distribution in Copper A-C Arcs

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Synopsis.—A previous paper on a-c arcs in air between copper electrodes showed the influence of circuit constants in determining the rise of voltage across the electrodes during the reignition period of cyclic current zero. This paper gives the distribution of potential throughout the arc space between the electrodes during the reignition

period, and shows that during that time the potential drop is concentrated largely in the space adjacent to the cathode, the major portion of the arc space is free from potential gradient, and the potential distribution is measurable with fidelity by means of inserted probes.

INTRODUCTION

SEVERAL articles of recent years have shown the importance of the problem of reignition of a-c arcs in air between copper electrodes.¹ Recently, two of the present authors described the conditions controlling the rate of voltage rise across the arc electrodes during the interval of cyclic current zero and its relation to the rate of deionization of the gap.² The arc reignites if the circuit constants permit the arc electrodes to experience a voltage rise of rapidity sufficient to overcome the growing dielectric strength of the arc space.

The present article shows the distribution of potential between the electrodes during the reignition period when the current is zero and emphasizes the possibilities and limitations of probe methods of measurement of this potential distribution.

One or more probes is introduced into the arc space, and by connecting one or another of the probes or the electrodes to a cathode ray oscillograph the changes in potential that take place in the arc space and near both electrodes during the reignition period are recorded.

The first outstanding result of the investigation is that, during the period when the arc current is passing through its cyclic zero and the electrode voltage is changing rapidly and reversing its polarity, the great percentage of the electrode voltage is to be found in a drop in potential at that electrode which is, for the time being, the cathode.

Furthermore, it appears that under appropriate conditions probe methods of measuring the rapidly changing potential distribution are justifiable.

THE CIRCUIT AND THE ELECTRODE POTENTIAL

The circuit shown in Fig. 1, like that used in the earlier investigation,² comprises a 702-volt 60-cycle transformer connected to the arc electrodes through a contactor and an air core inductance of $L = 0.068$ henry whose distributed capacity is $610 \mu\text{mf}$; $R = 1,000$ ohms is shunted across the arc electrodes to delay voltage recovery. The arc current of approximately

27 amps rms lags very nearly 90 degrees behind the transformer voltage. The electrodes are flat parallel-faced copper plates placed $\frac{3}{4}$ inch apart.

The arc is started by the burning of a No. 40 copper-wire fuse. The contactor is closed at the instant corresponding to zero steady-state current, thus avoiding a transient, and the arc is initiated when the fuse burns, about one-quarter cycle later. The cathode ray oscillograph records the electrode or probe-to-electrode voltage at the end of the second half-cycle of current.

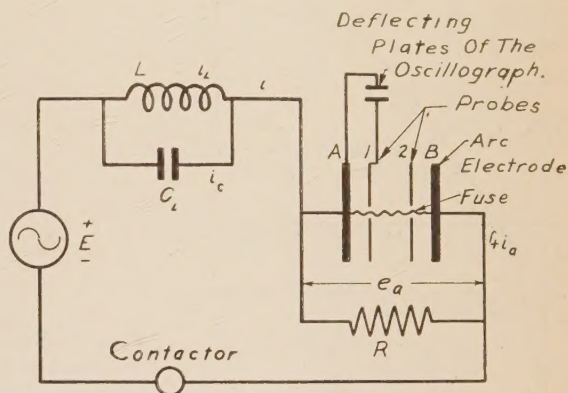


FIG. 1—THE CIRCUIT

$E = 992$ volts = peak of 702-volt 60-cycle circuit voltage

$L = 0.068$ henry

$C_L = 610 \mu\text{mf}$

$R = 1,000$ ohms

$i = 27$ amp rms approximately

$e_a = 992 - 1,131 e^{-0.0147t} + 64 e^{-1.64t}$ volts. (Applicable during the reignition period only)

$t =$ microseconds after current zero

Except for the first few microseconds after current zero, the voltage across the electrodes rises according to the equation²

$$e_a = 992 - 1131 e^{-0.0174t} + 64 e^{-1.64t} \quad (1)$$

This is shown in Fig. 2 as a broken line; the heavy line is a replot of values taken from the oscillogram of Fig. 7A. A composite picture made from many oscillograms will check the broken line much more closely than the particular oscillogram shown in Fig. 2.

In the previous paper² it has been shown that for low values of resistance shunting the arc, the negative voltage dip does not follow the circuit equation, but that after a brief interval (in this case about 5 micro-

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1. For references see bibliography.

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seconds) the electrode voltage does follow the circuit equation developed from the circuit constants. At approximately 415 volts and 42 microseconds after "arc-failure" the arc space develops a glow discharge that lasts for 24 microseconds before the arc in the new direction begins. These values are typical, but of course there are variations from arc to arc in the magnitudes of the negative voltage dip, the reignition voltage, and the duration of the glow.

PROBE MEASUREMENTS

The aims of these experiments have been to measure the distribution of the potential throughout the arc space during the period of current zero, and to show that this potential may be measured by the introduction of suitably shaped copper probes. The probes were thin copper plates placed between the electrodes, and had circular holes through which the arc might play. The probe finally adopted (Fig. 3) was made of sheet copper

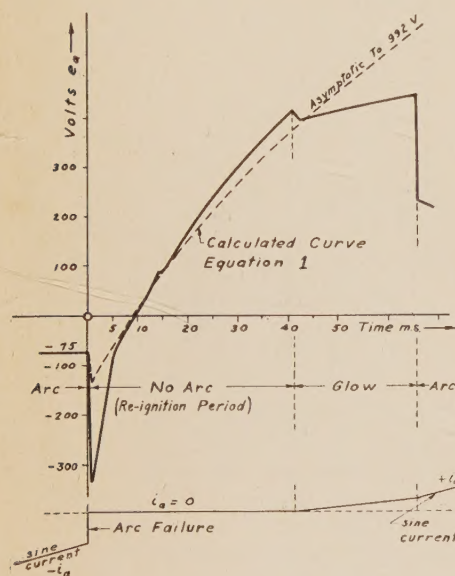


FIG. 2—VOLTAGE ACROSS ARC ELECTRODES. HEAVY LINE IS A PLOT OF OSCILLOGRAM OF FIG. 7A

1/64 inch thick, 1 inch square, with a hole 1/6 inch in diameter. The slot leading horizontally from the edge of the hole permitted insertion of the copper-wire fuse used to start the arc.

Probes having hole diameters between 0.21 inch and 0.12 inch gave satisfactory and practically identical results. The sum of cathode-to-probe and probe-to-anode voltages equalled the cathode-to-anode voltage. Furthermore, the cathode-to-anode voltage gave the same record whether the probes were present or not. Probes with larger holes failed to measure the voltage, while with smaller holes the arc failed to restrike. Changes in overall dimensions of the probes had no effect upon the oscillographic records.

The simplest procedure in using a probe to measure a potential difference between an electrode and a point in an ionized gas is to connect the electrode and the probe to the two plates of a cathode ray oscillograph. As a first approximation it may be assumed that the

oscillograph will respond faithfully to very rapid changes in potential without requiring the probe to draw any appreciable current from the ionized region in which it is placed.

A probe that does not carry current acquires a potential only approximately the same as that of the adjacent ionized gas. By measuring the small amounts of current drawn by probes at *controlled potentials* Lang-

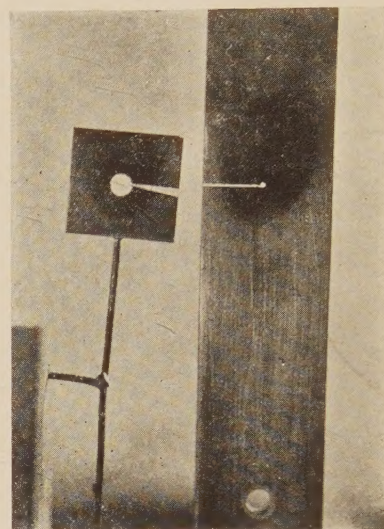


FIG. 3—PHOTOGRAPH OF PROBE AND ELECTRODE

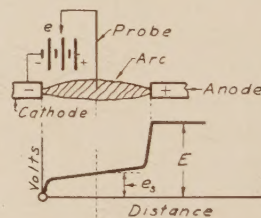
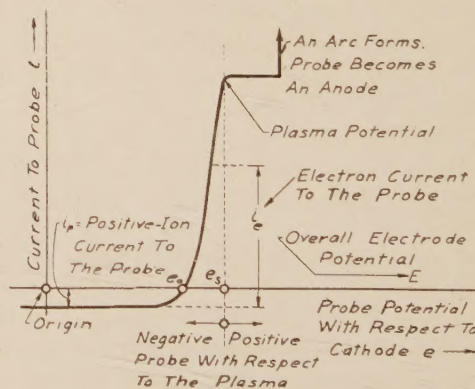


FIG. 4—VOLT-AMPERE CHARACTERISTIC OF A PROBE PLACED IN A STEADY DISCHARGE



muir determined the difference between a non-current-carrying probe's potential and that of the adjacent ionized gas in discharges at low pressures, and his method has been used by other experimenters^{5,7,9} with arcs at atmospheric pressure.

The lower curve of Fig. 4 is typical of the volt-ampere characteristics of controlled-potential probes placed in what Langmuir terms "plasma" regions, which in general include all except the boundary regions of a

great many arc and glow discharges. The cathode potential is considered zero, and e_s is the potential in the gas of the discharge at the point where the probe is located; e_0 , the potential of the probe when it is carrying no current, is measured by the cathode ray oscillograph. According to experiments by Nottingham,⁵ Bramhall,⁹ and Forbes⁷ the difference of potential $e_s - e_0$ is of the order of 10 to 15 volts in a copper arc at atmospheric pressure. This is the error in measurement to be expected when using a probe which draws no current. When measuring potentials which run up into several hundred volts this error is negligible.

With a very low probe potential ($e < e_0$), the current is exceedingly small and consists entirely of a flow of positive ions from the ionized gas to the probe. Except at very low negative probe potentials, there is, besides the positive-ion current, an electron current flow to the probe in spite of its negative potential, because some of the electrons possessing higher energies overcome the potential difference between the plasma and the probe by virtue of the random motions of their thermal agitation. At $e = e_0$ this electron current is equal exactly to the positive-ion current, so that the net current to the probe is zero; if the probe potential is made higher the electron current rises rapidly. At $e = e_s$ the plasma and the probe have the same potential and there no longer is any hindrance to electron movement toward the probe.

A moderate rise in potential of the probe above that of the plasma ($e > e_s$) does not materially increase the number of electrons reaching it over the number that arrives due to random movement only, because of the appearance of a negative space-charge near the probe surface; hence the characteristic just to the right of e_s is horizontal. When the probe potential becomes markedly higher (5 to 25 volts) than that of the plasma, the current rises sharply to a value determined by external circuit conditions. Beyond this point the arc strikes to the probe if circuit conditions permit.

Experimental investigations^{5,7,9} of the copper d-c arc in air have shown that the essential theoretical conditions⁶ for the existence of a plasma are fulfilled—*e.g.*, a relatively small electric field and equal concentrations of positive and negative charges. There is no reason for assuming that these conditions do not apply to the a-c arc. When the a-c arc current fails and the reignition period is reached the simplest assumption is that the arc space still contains a plasma but without any current flow. This assumption is borne out by overall voltage oscillograms of long arcs, 10 to 15 inch, taken during the reignition period, which show that during this time the overall voltage of a long ionized space substantially is that of a short space, indicating that the major portion of the ionized space is free from potential gradient—a condition that can prevail only if a plasma exists during the reignition period.

The probes used by the authors measure the potential at points outside the furthest radius of the arc-core

proper and make them after current flow has ceased entirely. But studies⁸ on dynamic a-c arc characteristics have shown that the establishment and decay of the arc-stream require considerable time, so that as the a-c current decreases from its maximum to zero the degree and extent of ionization persists over a much larger volume than that needed for the decreasing current flow. Further, unpublished work done by A. D. Forbes⁷ under the direction of two of the authors indicates that the hot gases surrounding the arc-core fulfill the plasma conditions for a radial distance of several millimeters beyond the optically well-defined arc-core boundary, and that the potential of this surrounding plasma is lower than that of the arc-core itself only by a very few volts. The only reasonable conclusion is that the entire gaseous envelope is a persistent plasma

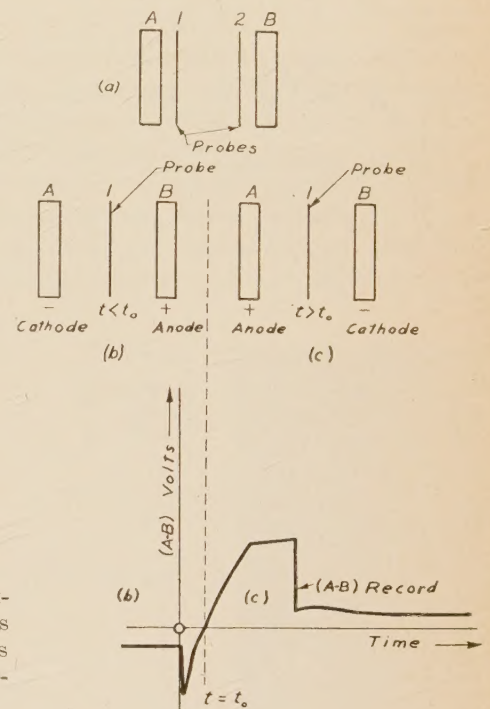


FIG. 5—POLARITIES OF PROBES AND ELECTRODES AT DIFFERENT INSTANTS

region, hence probe measurements are valid during the reignition period.

DISTRIBUTION OF POTENTIAL THROUGH ARC SPACE

In the experiments first undertaken two probes were used, one placed near each electrode, as illustrated in Fig. 5a. Electrode A served always as the "old cathode," hence also as the "new anode," the polarity change occurring at time $t = t_0$ of Fig. 5. The probe placed near the A electrode was called No. 1, that near the B electrode No. 2, and the measured voltages then identified as $(A - B)$, $(A - 1)$, $(A - 2)$ and $(2 - B)$. It was soon discovered that the probe-to-probe potential during the reignition period was very small, even with arcs of 10 inch and 15 inch length. With only very slight exceptions, the difference of potential between the electrodes is confined, during the reignition period, to thin regions adjacent to each electrode.

Therefore, in later experiments only one probe was used, placed half-way between the electrodes. With this arrangement the voltage oscillogram ($A - 1$) reveals the potential changes adjacent to the surface of the A electrode, and ($1 - B$) that adjacent to the B electrode. Figs. 5b and 5c illustrate the polarity relationships between the electrodes before and after time $t = t_0$.

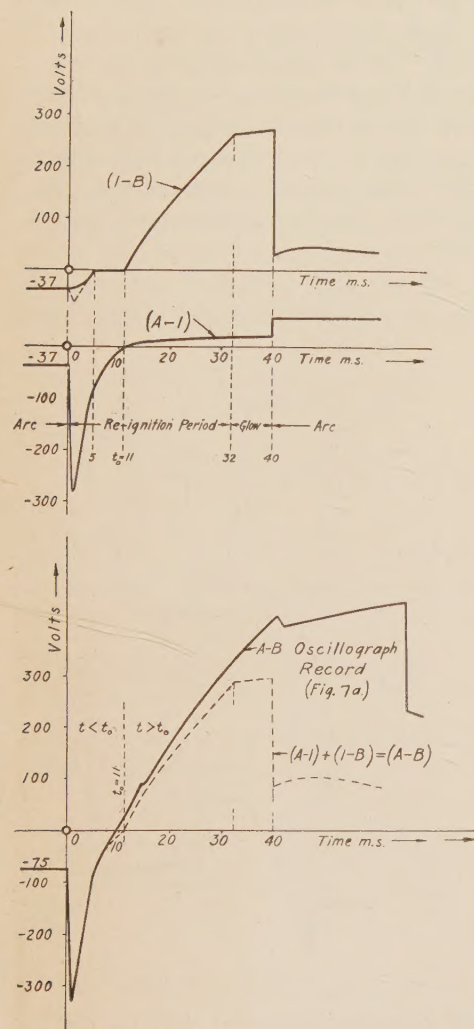


FIG. 6—POTENTIAL DISTRIBUTION THROUGH THE ARC SPACE

Fig. 6, drawn to scale, shows the potential drops ($A - 1$) from electrode A to probe, ($1 - B$) from probe to electrode B , and the sum of these two voltages, ($A - 1$) + ($1 - B$). This sum should equal the actual ($A - B$) voltage, measured from electrode A to electrode B , at every instant, and to illustrate the nature of this check, a typical ($A - B$) oscillograph record is drawn on the same graph as the ($A - 1$) + ($1 - B$) sum. It should be understood that the reignition voltage and the length of the glow period vary from arc to arc. The ($A - 1$), ($1 - B$) values and their sum ($A - 1$) + ($1 - B$) are typical values taken from the study of many oscillograms, while the ($A - B$) oscillograph record is the record of only one arc.

Prior to $t = 0$, (see Fig. 6) the arc current being negative, the ($A - 1$) and ($1 - B$) voltages are approxi-

mately 37 volts each, giving a 75-volt electrode drop ($A - B$). At $t = 0$, the arc current drops from about 0.3 ampere to zero with extreme rapidity. From $t = 0$ to $t = 5$ microseconds the electrode voltage passes through a negative dip; most of this voltage is located in a thin layer adjacent to electrode A which is, for the time being, the cathode. The probe-to-anode voltage ($1 - B$) during this period may show a slight dip and then approach zero or may approach zero without any dip. At $t = 5$ the electrode voltage changes slope abruptly and thereafter follows closely the equation of circuit voltage rise (equation 1). From $t = 5$ to $t = t_0 = 11$ microseconds, the electrode voltage is found almost entirely at the cathode A , the probe-to-anode potential ($1 - B$) remaining nearly zero.

At $t = t_0 = 11$ the electrode voltage passes through its zero value. Thereafter A is the anode and B the cathode, and most of the voltage again is found at the cathode, though the anode drop appears to be of the order of 15 to 20 volts. At $t = 32$ the reignition period ends with the formation of a self-sustaining glow discharge during which the current increases slowly from zero in the positive direction. At $t = 40$ an arc is formed. The electrode and cathode voltages, ($A - B$) and ($1 - B$), drop rapidly while the current grows in a sinusoidal manner. In the change from glow to arc the

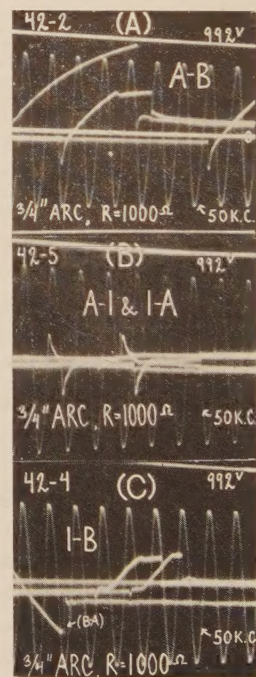


FIG. 7—POTENTIAL VARIATION WITH TIME

- A. Across the electrodes
- B. In the arc space near the A electrode
- C. In the arc space near the B electrode

anode voltage ($A - 1$) may increase suddenly from 20 to about 50 volts.

Figs. 7A, B and C are cathode ray oscillograms of the voltages ($A - B$), ($A - 1$) and ($1 - B$). The two pairs of ($A - 1$) voltages have been reversed with respect to each other in order to establish the position of the zero voltage line.

Fig. 8, derived from Fig. 6, represents the potential distribution in the arc region at various moments of

time. It illustrates the absence during the reignition period of appreciable potential gradient except adjacent to the electrodes. A number of oscillograms under a variety of conditions were taken with two probes, one close to each electrode, in an attempt to discover a substantial potential gradient in the middle region when the voltage approaches reignition values, but so far the results have been entirely negative, even in

PROBE CURRENT REQUIREMENTS

It has been shown that the difference ($e_s - e_0$) between the voltage acquired by the probe and that of the plasma is so small as to be of no consequence for the immediate purpose. To justify probe measurements it also is necessary to show that the current to the probe is sufficient to make the potential of the capacity represented by the leads and deflecting plates of the cathode ray oscillograph follow accurately the variations in plasma potential, and to supply any ionization or leakage current that may flow between the deflecting plates of the oscillograph. The equation representing the charging current that must flow to the cathode ray oscillograph plates is

$$i_p = C_p \frac{de}{dt}$$

where C_p is the capacity of the measuring circuit consisting of probes, leads, and oscillograph deflecting plates, de/dt is the rate of change of voltage between the plates, and i_p is the charging current to the capacity C_p .

The maximum rate of change of voltage to be measured occurs at the beginning of the negative dip of the (A - 1) pictures. Here the plasma is becoming very rapidly positive with respect to the A electrode, hence

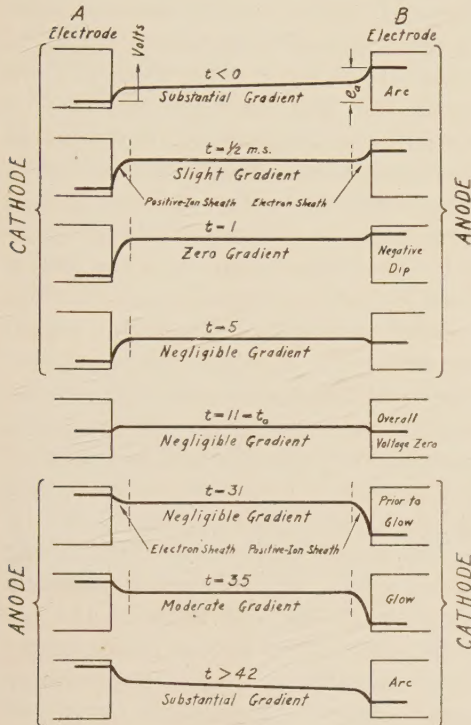


FIG. 8—POTENTIAL DISTRIBUTION THROUGH THE ARC SPACE

the case of very long arcs failing to reignite. The oscillograms of Fig. 9 are selected to illustrate this fact. Fig. 9B is a cyclogram; horizontally it measures the voltage (A - B) between the main electrodes, and vertically the voltage (1 - 2) between the two probes. At no time except prior to current zero and after reignition does the voltage (1 - 2) have any appreciable value.

Fig. 9C measures horizontally the voltage (A - B) and vertically the voltage (2 - B). Following the negative voltage dip the trace is a 45-degree line, indicating that nearly all of the voltage drop in the arc region up to the moment of reignition occurs at the surface of the cathode. Figs. 9A and 9B both show that while the (1 - 2) voltage is very small during the reignition period it grows to a considerable magnitude after the arc strikes.

These oscillograms show definitely that in the arcs used in these experiments the reignition process is one that is initiated in a thin layer of gas adjacent to the cathode surface. The variations in reignition voltage that have been observed in the authors' previous experiments therefore are a result of variation in the condition of a thin insulating layer of gas adjacent to the cathode.

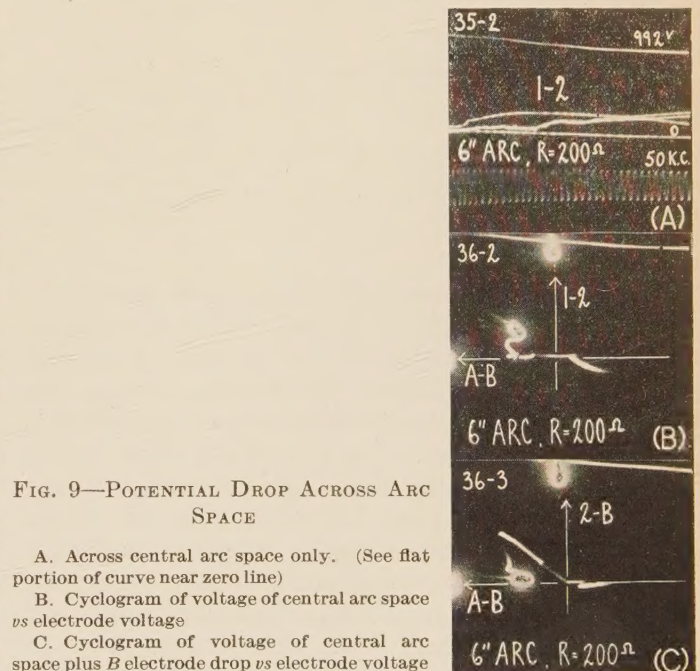


FIG. 9—POTENTIAL DROP ACROSS ARC SPACE

- A. Across central arc space only. (See flat portion of curve near zero line)
- B. Cyclogram of voltage of central arc space vs electrode voltage
- C. Cyclogram of voltage of central arc space plus B electrode drop vs electrode voltage

to follow the change the probe must acquire a positive charge. This it can do only by means of the very small positive-ion current from the plasma; if the positive-ion current is too small relative to C_p the oscillograph will not give an accurate record.

If it is assumed that during the negative dip the entire voltage appears between cathode and probe (this is the severest possible assumption) the rate of change

of potential to which the probe must respond can be calculated as follows:

$$\frac{de}{dt} = \frac{I_1}{C_L} = \frac{0.3 \text{ (approximately)}}{610 \times 10^{-12}} \\ = 0.5 \times 10^9 \text{ volts per second} \quad (2)$$

The capacity C_p used was not over 5 micromicrofarads. The 0.3-ampere figure used for I_1 is selected as the largest value of arc-failure current observed by the authors under similar conditions.² Using these figures the required charging current to the plates is

$$i_p = 0.5 \times 10^9 \times 5 \times 10^{-12} = 2.5 \times 10^{-3} \text{ amperes.} \quad (3)$$

Since the ionization current and the leakage current between the oscillograph plates of the high-vacuum oscillograph used probably are very much smaller than this, the capacity current is the controlling requirement.

The results of experiments by Nottingham⁵ and by Bramhall⁹ permit a rough estimate of positive-ion current density; values range from around 0.005 amp per sq cm at a distance of two millimeters from the center of an 8-ampere arc about one-half centimeter long to from 10 to 30 times that nearer the center of the core.

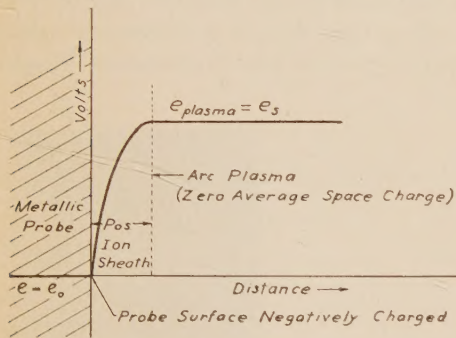


FIG. 10—POTENTIAL DISTRIBUTION THROUGH A POSITIVE-ION SHEATH

The arc used in the authors' reignition tests was nearly 2 centimeters long, and at its peak carried 38 amperes. It seems reasonable to expect that the positive-ion current density in the plasma that persists through the reignition period is at least 0.005 amp per sq cm and may substantially be larger. The area of the probe that is blackened by the heat of the arc indicates that the effective area of the probe in contact with the plasma may have been as large as 3 sq cm, whereas it need only be one-half sq cm to provide, at 0.005 amp per sq cm, the charging current required by the oscillograph under the most exacting conditions. Since these figures are very approximate, their chief value is to indicate that even at the beginning of the negative dip in the (A - 1) picture the equipment used was working within the limit of accurate response.

The preceding discussion indicates only a reasonable probability that probe measurements should be successful. A necessary experimental check consists of tests to determine whether the voltage from cathode to probe plus that from probe to anode actually is equal to the voltage from cathode to anode. Tests of this kind

were made on a variety of shapes and sizes of probes, leading finally to the choice of the probe shown in Fig. 3, which gave results that satisfied the experimental check required.

ELECTRON MOVEMENT DURING REIGNITION PERIOD

The explanation for the potential distributions that are revealed by experiment is apparent if the probe-like nature of the electrode surfaces during the reignition period is recognized. After current zero and prior to reignition both electrodes are adjacent to a plasma region, yet little or no current passes from either of them to or from the plasma; the same statement applies to a probe placed between the electrodes. There is no essential difference then between electronic behavior in the boundary region adjacent to the probe and that adjacent to the main electrode surfaces. The lower part of Fig. 4 applies to the electrodes as well as to the probes during the reignition period. The potential distribution within the positive space-charge boundary region adjacent to either electrode or probe surface when negative with respect to the plasma has the general form represented by the curve of Fig. 10. The boundary region, which occupies a very thin layer of gas is called a positive-ion sheath because of the absence of electrons, which are kept out by the retarding field. The potential line is straight and horizontal in the probe and in the plasma, for in these regions there neither is potential gradient nor space-charge. The curvature of the potential line within the positive-ion-sheath indicates the presence of a positive space-charge density proportional to the rate of change of slope of the potential curve, the total positive space-charge being related closely to the overall sheath voltage.

Immediately after the arc current fails circuit conditions require an increase of overall arc voltage in the old direction; it reaches about 300 volts at $t = 1$. From Fig. 4 it is seen that if the potential of a probe-like surface adjacent to a plasma is raised to more than perhaps 20 volts above the plasma potential the probe becomes a new anode of the discharge, that is, it begins to draw electrons from the discharge at a substantial rate dependent upon circuit conditions. This circumstance limits the potential difference between the arc region and whichever of the two electrodes is positive with respect to it to something in the neighborhood of 20 volts.

Therefore, the cathode-to-probe drop must be 20 volts less than the overall potential (A - B). Since during most of the reignition period the (A - B) voltage is much greater than 20 volts, it follows that the great percentage of the (A - B) voltage is to be found at the cathode, as is shown to be the case in Fig. 6.

During the period from $t = 0$ to $t = 1 \mu\text{sec}$ the overall voltage is rapidly increasing, hence the voltage drop (A - 1) and its associated positive space-charge near the more negative electrode must increase very rapidly. (See the $t = 1/2$ graph of Fig. 8.) With a sufficiently

rapid change in overall voltage the electron current flow taking place from the sheath at the cathode through the arc space to the anode and out into the metallic circuit may be comparable with the normal arc current in magnitude. During such a time the positive-ion sheath at the cathode may be thought of as a condenser that is being charged, except that the charge probably is not directly proportional to the difference of potential. There then is a slight potential gradient throughout the arc region, and a normal anode fall of potential at the more positive electrode, just as is the case when arc current in the ordinary sense is flowing.

By contrast the $t = 5$ graph of Fig. 8 illustrates the condition existing with a stationary or decreasing overall potential; this figure is strikingly similar to Fig. 3 of a recent article by Langmuir⁶ illustrating the "trapping" of electrons in a plasma region containing a potential maximum.

CONCLUSION

The authors feel that they have performed three tasks: first, to throw some light on the electronic activity that occurs during the reignition period of an a-c copper arc in air; second, to show that except adjacent to the electrodes the arc space possesses a negligible potential gradient during the reignition period; and third, to show that probe methods of measurement of

the potential distribution are justified if the probes are used under conditions which do not violate the inherent limitations of the probe method.

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